CHANGES TO THE GFDL HURRICANE FORECAST SYSTEM FOR 2001 INCLUDING IMPLEMENTATION OF THE GFDL/URI HURRICANE-OCEAN COUPLED MODEL

Morris A. Bender
Isaac Ginis *
Timothy P. Marchok **
Robert E. Tuleya

Geophysical Fluid Dynamics Laboratory, NOAA Princeton, New Jersey 08542 (Tel. 609-452-6559 FAX 609-987-5063, e-mail: mb@gfdl.gov)

Graduate School of Oceanography *
University of Rhode Island
SAIC/NCEP **

1.) Introduction

Since 1995, the GFDL Hurricane Prediction System has provided operational guidance for forecasters at the National Hurricane Center (NHC) in both the Atlantic and East Pacific basins (Kurihara, Tuleya and Bender 1998, hereafter referred to as KTB). In addition, a version of the GFDL model (GFDN) has been used by the Navy to provide operational guidance for storms in most of the other ocean basins as well (Rennick 1999). Although the model has shown great skill in track prediction, the GFDL Hurricane Prediction System exhibits small track biases and rather large intensity biases (Bender and Ginis 2000). Indeed, in spite of a steady improvement in tropical cyclone track forecasting over the last two decades (Lawrence et al. 1997), there still appears to be little skill in predicting hurricane intensity changes.

To help reduce the large intensity errors in the GFDL prediction system, an improved version of the GFDL model has been developed in which the forecast model has been coupled with a high-resolution version of the Princeton Ocean Model (POM). This new model has been run in parallel with the operational GFDL model during the past three hurricane seasons, and has demonstrated substantial improvements in the prediction of storm intensity, particularly measured by the storm's minimum sea level pressure, with a reduction of nearly 26% in the mean error.

Another intensity-related problem is that in strong wind conditions, the GFDL model's prediction of the low level wind has exhibited a large negative bias and poor pressure wind relationship, as the model tends to under-predict surface wind speeds for a given central pressure. To address this problem, another important change will also become operational in the 2001 hurricane season in which an equation for the prediction of turbulent kinetic energy is added to the diffusion parameterization. Tests have indicated that this results in a significantly improved vertical profile of wind speed in the boundary layer and a much improved pressure wind relationship. Finally, changes were also incorporated into the initialization of the model's specified vortex (Kurihara, Bender and Ross 1993 hereafter referred to as KBR), which has lead to an initial storm intensity that more closely matches the observed value and has also decreased the tendency of the model to over-intensify weak systems during the first 12-24 hours of the forecast.

Besides improving intensity forecasts, it is important that any changes do not lead to an appreciable degradation in the track forecasts. It is encouraging that tests with this entire package have shown a decrease in the average track error of 5-10% in the 24 to 72h hour time period.

2.) Outline of Atmospheric Model and changes implemented in 2001

The GFDL multiply-nested moveable mesh model has been described in previous publications (e.g., Kurihara et. al 1995 Kurihara et. al 1998) and will only briefly be outlined here. The model is a primitive equation model formulated in latitude, longitude, and sigma coordinates, with 18 vertical sigma levels. The grid system for each of the triply nested meshes is summarized in Table 1.

TABLE 1. Grid system of the triply-nested mesh hurricane model.

Mesh	Grid resolution (degree)	Domain size: Longitude (deg)	(points)	Latitude (deg)	(points)	Time step (sec)
1	1	75	(75)	75	(75)	90
2	1/3	11	(33)	11	(33)	30
3	1/6	5	(30)	5	(30)	15

The model physics of the current operational hurricane model include cumulus parameterization described by Kurihara (1973) with some additional modifications (Kurihara and Bender, 1980, appendix C) a Monin-Obukhov scheme for the surface flux calculation and the Mellor and Yamada (1974) level-two turbulence closure scheme for the vertical diffusion, with a background diffusion coefficient added. As described by Tuleya (1994), the Schwarzkopf and Fels (1991) infrared and Lacis and Hansen (1974) solar radiation parameterization were also incorporated, with interactive radiative effects of clouds and a diurnal radiation cycle. The land surface temperature is computed by an energy equation containing a soil layer.

In the upgraded 2001 system, **the vertical diffusion will be upgraded to a level 2.5 Mellor-Yamada turbulent closure scheme.** In this formulation, an equation for the prediction of turbulent kinetic energy is added to the diffusion parameterization. The diffusion coefficients K_M and K_H are then computed using the turbulent kinetic energy (b^2) computed by equation (4:23) of Miyakoda and Sirutis (1977). Near the region of maximum winds this scheme significantly enhances the transfer of momentum from above, leading to a more vertically mixed hurricane boundary layer with higher surface winds. This corresponds more closely with recent results observed using GPS sondes. In addition, in the upgraded system model surface winds will again be estimated by the lowest model layer as in TPB # 424 (1995), since it is evident that the reduction to 10m by the Monin-Obukhov formulation is not valid. Together, these changes lead to a much improved pressure-wind relationship and improved wind forecasts as will be shown later

3.) Outline of Atmospheric Initialization and changes implemented in 001

In this section, changes that will be made to the atmospheric initialization will be described in detail. As outlined in KTB, the initial condition for the atmospheric model is obtained from the current AVN which is interpolated onto each of the three nested meshes. Two filters are used to remove the original vortex from the AVN analysis following the procedure outlined in KBR and modified by Kurihara, Bender, Tuleya, and Ross 1995 (hereafter referred to as KBTR).

First, using a scale selective filter, the AVN fields (A) of wind, temperature and surface pressure are partitioned into a large-scale component called the basic field (B) and the deviation field denoted as the disturbance field (D):

$$A = B + D \qquad (1)$$

Next, using a second filter, the disturbance field is separated into the hurricane component (H) which will be removed from the analysis and a non-hurricane component (NH) that should be retained. The environmental field is then obtained by combining the non-hurricane component of the disturbance field with the basic field over the entire model domain.

In the filtering technique it is assumed that the hurricane component (H) that is to be removed is entirely confined within a filter domain (ro) so that the region of the global analysis beyond ro by definition remains unchanged. The extent of the filter domain (ro) is computed at 24 radial points surrounding the AVN vortex, determined by testing the radial profiles of the tangential component of the disturbance wind, from the vortex center outward. Once ro is determined at each of the 24 azimuthal angles, it was then multiplied by 1.25 (r_{fact}) to guarantee that the hurricane component is entirely contained within the filter domain. It was found that with the new AVN analysis, the value of $r_{fact,}$ could be reduced with the analysis vortex still adequately removed. The obvious advantage of reducing the size of the filter domain is to lessen the possibility of removing important features from the original global analysis. In extensive tests it was determined that a value of 1.1 appeared optimal for r_{fact} both by the reduction of the track error in the test cases and in careful analysis of the resulting fields in these cases. **Hence, in the new upgraded GFDL forecast system, we have changed the value of r_{fact} from 1.25 to 1.1.**

As summarized in KBR, during the next step of the initialization, a model-compatible specified vortex is generated and inserted back on to the environmental field at the correct storm position. The specified vortex is generated from the time integration of an axi-symmetric version of the hurricane prediction model. During the integration, the tangential component of wind is gradually forced over a 60h time period toward a target profile based on the storm observations provided by the National Hurricane Center (NHC) in 4 quadrants surrounding the storm. Four modifications were made to enable the initial wind field to more closely match with the correct observed storm intensity.

(1.) The tangential wind is forced toward the target profile at the model level ktop (defined as the model sigma level closest to 850 hPa). The environmental flow at each observation location is subtracted from the total observed wind to obtain the wind component related to the vortex. However, since the observed wind data available are reported surface values, in the present system they are multiplied by an empirically obtained factor f (presently 1.30) to estimate the tangential component at level ktop. However, the value of f tended to be too large and a more reasonable value of 1.20 has been tested and found to yield positive improvements. **In the new upgraded GFDL forecast system, the value of f has been changed from 1.30 to the new value of 1.20.**

(2.) In the previous system, the forcing of the tangential component to the target value was eliminated during the last hour of the time integration of the axi-symmetric model, to reduce any imbalance that may have developed in the model fields due to the forcing. However, careful analysis indicated that this could cause a large spin-up or spin-down of the vortex due to the absence of any environmental conditions in the vortex spin-up that may impact the storm intensity in the three dimensional model. By retaining the forcing throughout the entire period of the integration, it was found that the final winds were closer to the targeted values. **In the new upgraded GFDL forecast system, the forcing of the tangential winds to the target profile is retained throughout the entire axi-symmetric integration.**

(3.) In general, the axi-symmetric model is integrated to 60h. The integration is terminated earlier if the surface pressure difference ($p_{diff)}$ between the minimum surface pressure and the value in the outer region of the storm exceeded the observed pressure difference plus an additional factor Dp where

$$Dp = \min(p_{max}, a + b\, p_{piff}) \qquad a = 1 \text{ hPa} \qquad b = .25, \qquad p_{max} = 10 \text{ hPa} \qquad (2)$$

However, it was found that in some cases this lead to storms that were initially much deeper then observed. To correct this problem, in the new upgraded GFDL forecast system, we have reduced this correction factor (Dp) by changing the values of the constants b and p_{max} to the values **.05** and **4 hPa**, respectively.

(4.) At the beginning of the current initialization, the axi-symmetric vortex was initialized with the environmental values of the moisture ($M_E = M_{Basic} + M_{Dis} - M_{Hurr}$) and temperature at the storm center. At the end of the axi-symmetric spin-up, the deviation of the water vapor mixing ratio at each point from the value at the outer storm region (M_{Axi}) was then computed (e.g., Fig. 3 of KBR). This value was added entirely back onto the environmental moisture field as a function of distance from the storm center to obtain the final moisture (M_F) at the start of the integration:

$$M_F = b * M_{Axi} + M_E \quad (b = 1 \text{ over water: } b = .5 \text{ over land})$$
(3)

However, it was found that this often lead to excessive amounts of humidity in the storm region initially, especially for weak storms. This likely contributed to the positive intensity bias during the first 12-24 hours of the forecast, as the vortex often began to rapidly spin-up at the start of the forecast. To help reduce this false spin-up, the value of b was reduced so that the initial humidity fields in the storm region would have more reasonable values. For well developed and more intense storms, the value of b would be expected to be larger which was confirmed by examining the storm structure of mature storms after many hours of integration. Since the actual value of b is somewhat arbitrary, the most reasonable approach was to make it a function of the observed intensity tendency over the previous 6 hours as well as the storm's current intensity determined by the central surface pressure. Taking these considerations into account we obtained the following formula for b as a function of the current observed storm intensity p_{cur} (hPa) and the observed intensity tendency over the last 6 hours (p_{tend}):

$$bi = \max(.35 , p_{base} + p_{tend} * a) \qquad p_{tend} = p_{old} - p_{curr} \quad a = .035 \tag{4}$$

$$b = \min(1.0, bi)$$

$$p_{base} = .5 + b_{int} \tag{5}$$

$$b_{int} = .4 \qquad p_{cur} < 960 \text{ hPa}$$

$$b_{int} = .4 * (985. - p_{cur})/25. \qquad 960 < p_{cur} < 985 \text{ hPa}$$

$$b_{int} = 0.0 \qquad p_{cur} > 985 \text{ hPa}$$

As seen in equation 4, b is bounded by the values of .35 and 1.0.

4.) Outline of the Ocean Coupled Model

The most substantial change to be implemented in the 2001 hurricane forecast system is the coupling of the GFDL forecast model with a high-resolution version of the Princeton Ocean Model (POM). The specific model details and experimental design have been outlined extensively in Bender and Ginis (2000), hereafter referred to as BG. For proper simulation of the ocean interaction, the ocean model should have a highly accurate representation of the upper ocean mixed layer physics, which has been clearly demonstrated by the Princeton Ocean Model (e.g., Blumberg and Mellor 1987). POM is a three-dimensional, primitive equation model with complete thermohaline dynamics, formulated with an ocean-bottom following, sigma vertical coordinate system and a free surface. The model employs a second-order turbulence closure scheme (Mellor and Yamada 1982). The momentum and thermodynamic equations are solved with the prognostic variables of free surface, potential temperature, salinity and velocity computed.

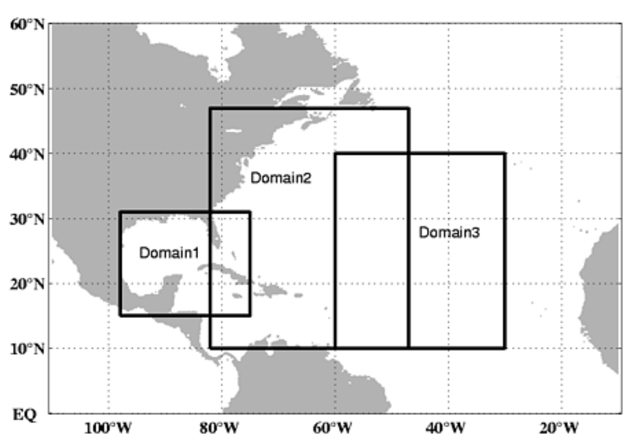

Figure 1 The three ocean model domains used in the GFDL hurricane-atmosphere coupled system.

In the current model configuration, three ocean model domains are used (Fig. 1). The grid resolution of each domain is 1/6° which matches the finest resolution of the innermost nest of the hurricane model. The first domain spans the region from 15° to 31°N and from 75 to 98°W and includes all of the Gulf of Mexico, the northwestern portion of the Caribbean Basin, and the southwest portion of the South Atlantic Bight. The second domain covers the western and central Atlantic area from 10° to 47°N and 48° to 82°W. The third domain covers the eastern most

Atlantic, from 10° to 40°N and from 60° to 30°W. Most of the Atlantic basin in which NHC has forecast responsibility, is covered by one of the three forecast domains. At the start of each forecast cycle, one of the three ocean domains is selected, based on the initial and 72h forecasted storm position. A summary of the vertical sigma levels for each of the three domains is presented in Table 2. The ocean interaction is only implemented in the Atlantic basin.

During the coupled forecast, the ocean model is integrated with a 1350 second time step while the three atmospheric meshes (Table 1) are integrated with time steps of 90, 30 and 15 seconds, respectively. Thus, the inner nest of the atmospheric model, with a corresponding 1/6° grid resolution, is integrated 90 times during one ocean time step. In the present system, the atmospheric wind stresses, the surface radiative fluxes and fluxes of sensible and latent heat are interpolated to a uniform 1/6° resolution and then passed from the atmospheric to the ocean domain. The ocean model is then integrated one time step in parallel with the atmospheric model which uses SSTs from the previous ocean step. At the time step in which synchronization of the atmospheric and the ocean model occurs the forecasted oceanic SSTs are passed to the atmosphere and interpolated to the nested grid domain and the updated atmospheric fluxes are passed to the ocean. In the present system, changes of surface stresses due to oceanic waves are ignored.

	Gulf of Mexico		Western and Eastern Atlantic	
k level	sigma	depth	sigma	depth
1	-0.0017	-5	-0.0009	-5
2	-0.0050	-15	-0.0027	-15
3	-0.0083	-25	-0.0045	-25
4	-0.0117	-35	-0.0064	-35
5	-0.0150	-45	-0.0082	-45
6	-0.0183	-55	-0.0100	-55
7	-0.0217	-65	-0.0118	-65
8	-0.0250	-75	-0.0141	-77.5
9	-0.0283	-85	-0.0168	-92.5
10	-0.0317	-95	-0.0200	-110
11	-0.0417	-125	-0.0245	-135
12	-0.0583	-175	-0.0318	-175
13	-0.0833	-250	-0.0455	-250
14	-0.1250	-375	-0.0682	-375
15	-0.1833	-550	-0.1000	-550
16	-0.2583	-775	-0.1409	-775
17	-0.3667	-1100	-0.2000	-1100
18	-0.5167	-1550	-0.2818	-1550
19	-0.7000	-2100	-0.3818	-2100
20	-0.9000	-2700	-0.5091	-2800
21	-1.0000	-3000	-0.6727	-3700
22			-0.8818	-4850
23			-1.0000	-5500

TABLE 2 Summary of vertical sigma levels in the ocean model and depths (m) in the deepest regions of the Gulf of Mexico and Eastern and Western Atlantic

5.) Ocean model initialization

A realistic ocean and hurricane initialization is critical for proper simulation of the ocean response in the coupled hurricane-ocean system. The current operational GFDL hurricane model uses the real-time SST data used in the operational AVN global analysis. The current resolution is too coarse to capture the large horizontal gradients of surface temperature on smaller spatial scales. In addition, the interaction between the ocean and the hurricane is also largely controlled by other properties of the upper ocean such as the mixed layer depth and stratification of the upper thermocline and upper ocean currents. Since there is no real-time sub-surface ocean data in advance of the hurricane operationally available, the ocean initialization relies on a diagnostic and prognostic spin-up of the ocean circulation using available climatological ocean data in combination with the real-time SST data. The initialization procedure, as outlined in detail in BG, consists of four steps. The ocean model is initialized by utilizing the monthly averaged profiles of temperature and salinity produced by the NAVOCEANO Generalized Digital

Environmental Model (GDEM). GDEM is an ocean climatology from the U.S. Navy observational database. The GDEM data provides the starting fields of temperature and salinity for the ocean model while the initial velocity field is set to zero. The ocean model is then integrated for one month in diagnostic model without surface forcing (e.g., holding the temperature and salinity constant while allowing the velocity field to evolve). This is followed by a three month prognostic run in which climatological GDEM temperatures and salinity at the sea surface is fixed in time and wind stress forcing from the Comprehensive Ocean-Atmosphere Data Sat is applied. In the operational implementation, the ocean condition at the end of this second step provides the data sets for each domain and for each month in which a hurricane forecast will be made. Next, once a day and for each of the three ocean domains, the upper ocean structure is adjusted to a more realistic pre-storm condition by assimilating the current sea surface temperature form the NCEP operational global analysis. In this step, the GDEM temperatures are replaced by the NCEP SSTs and a prognostic model integration is continued for 2 additional days, keeping the temperatures at the surface constant.

In the final ocean initialization step, the cold wake produced by the hurricane during the three-day period prior to the start of the forecast is generated. This step is necessary since the cold wake is not resolved is the current NCEP SST analysis. In this step the ocean model is forced by prescribed hurricane wind stress forcing using a hurricane axi-symmetric surface wind field generated from the National Hurricane Center storm message files. The surface stress is calculated using a simple bulk transfer formula with a drag coefficient. The ocean model is simply integrated with the above mentioned forcing, with the final ocean condition serving as the initial condition for both the atmospheric and ocean parts of the coupled model.

6.) Summary of Results

As mentioned previously, a coupled version of the previous operational GFDL system has been run in parallel with the operational uncoupled model during the past several years. This model has demonstrated significant improvement in storm intensity prediction, particularly in the forecast of the storm's minimum sea-level pressure compared to the current operational model. Fig. 2 shows an example of the improved intensity prediction during the very active 1999 hurricane season. Improvement in the intensity prediction is seen at each forecast time level, with an average reduction of 25% in the error of the forecasted central pressure. A similar result was found for the 1998 season, as well as in a limited number of test cases during the 1995-1997 season (Bender and Ginis 2000). Although some improvement in the prediction of the maximum low-level winds occurred with the coupled model, the overall improvement was limited because of

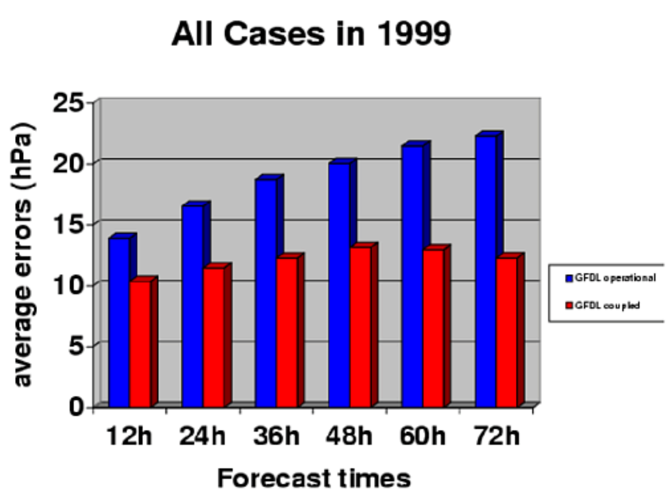

Figure 2 Average error in central pressure (hPa) at each forecast period for forecasts run during the 1999 hurricane system both for the operational (blue) and coupled (red) GFDL model

the tendency to under-predict the low-level wind in strong wind conditions with the present atmospheric model. However, this will be remedied with implementation of the changes outlined in sections 2 & 3 as shown in Fig. 3. Here the pressure wind relationship is shown (forecasted minimum pressure vs. forecasted low-level winds) for both the current operational GFDL model (blue) and the new system (red) tested from cases from the 1999 and 2000 hurricane season. The predicted low-level winds are now much closer to the observed values for a given central pressure, particularly for winds greater than 90 knots. In this set of cases, the model intensity prediction exhibited skill relative to SHIFOR at 24h, while the old GFDL system had skill only

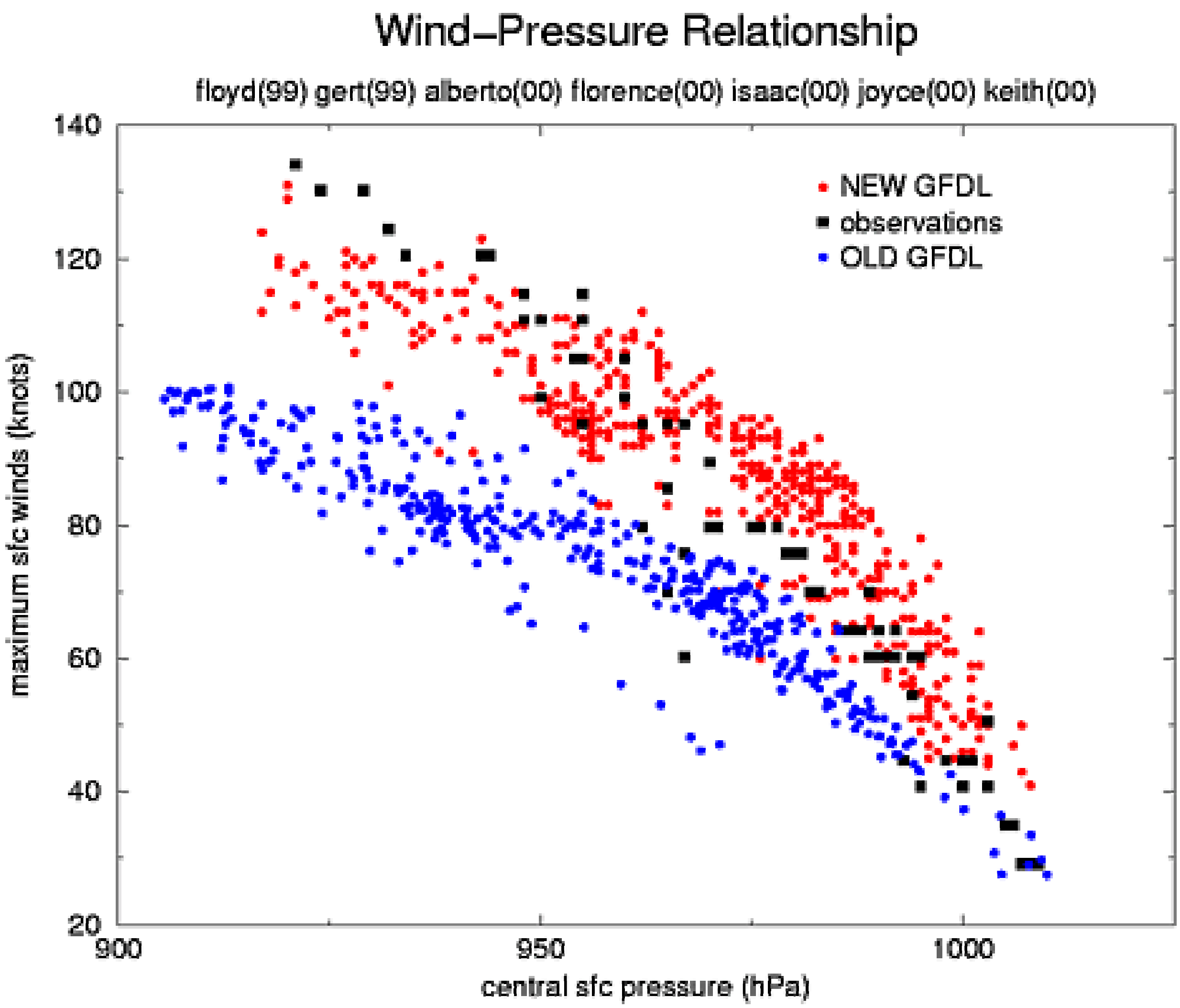

Figure 3 Plot of the pressure wind relationship (forecasted minimum pressure vs. forecasted low-level winds) for both the operational GFDL model (blue) and the new 2001 system (red) for test cases from the 1999 and 2000 hurricane season. The forecasted values at each of the forecasted time levels are plotted.

at the 72h time level (Fig. not shown).

Improvements in track were also demonstrated with the new GFDL system (Fig. 4) at all forecast time levels in test cases for storms that occurred during the two past hurricane seasons. In this first set of cases, both the new and old GFDL forecast systems were run from the current AVN

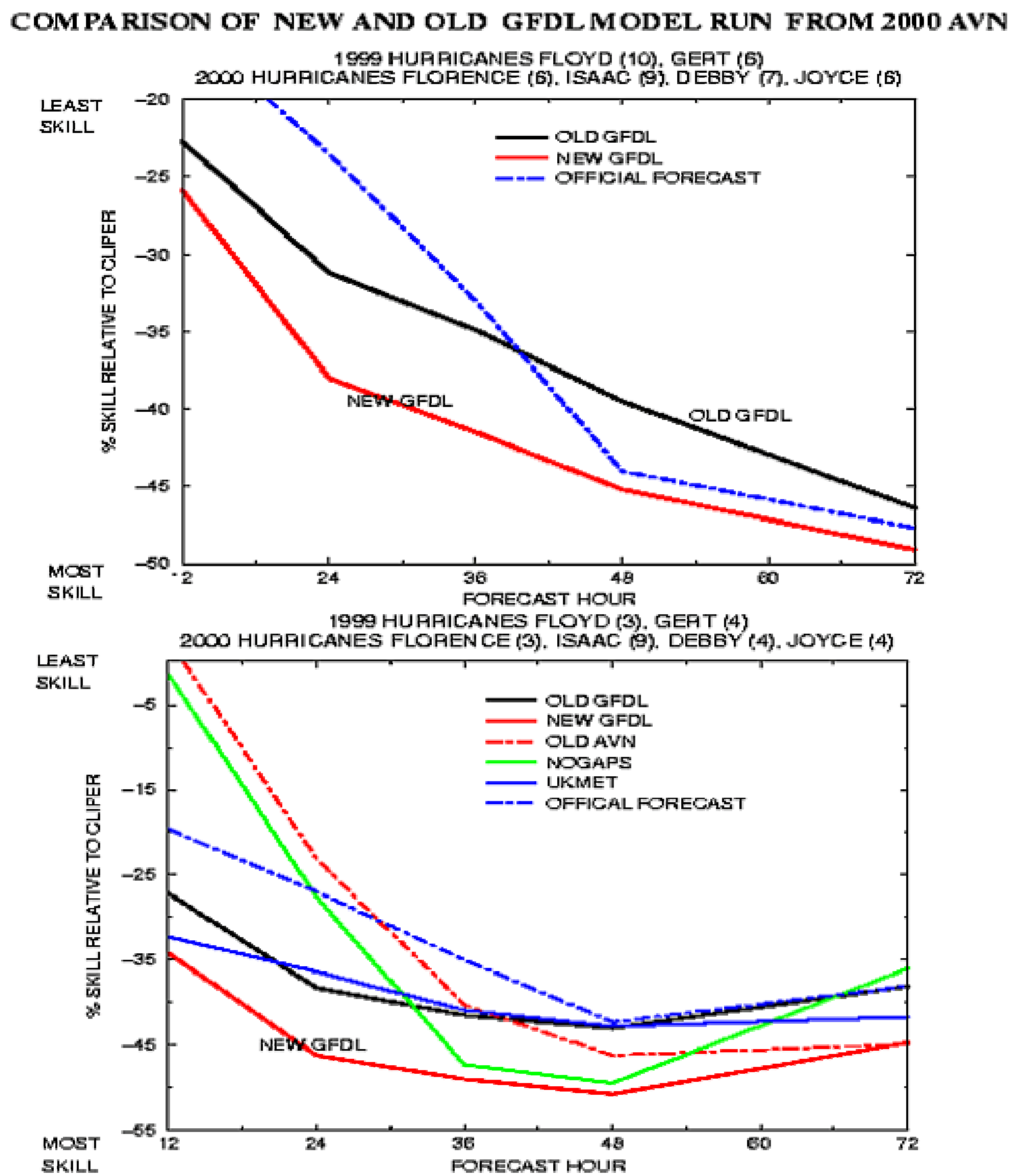

Figure 4 Plot of the track forecast skill relative to CLIPER (top), for both the operational (old) GFDL model (black), the new GFDL forecast system (red) and the official forecast (blue dashed) run for 44 test cases from the 1999 and 2000 hurricane season using the current 2000 AVN global analysis. A homogenous comparison (bottom) of the track forecast skill compared to several of the operational global models is also presented. The official forecast shown in this figure and in subsequent ones is presented as reference since it is based on 6 hour earlier model guidance.

global analysis. This enabled us to see the impact of the new changes to the GFDL model in 2001 in a wide variety of cases over the past two hurricane seasons. The improvements were statistically significant at the 24, 36 and 48h time period at the 95% confidence level, with a reduction in the average track error of about 10% at these time levels and 6% at 72h. It is interesting to note that in the homogenous comparison with several of the global models that also provided track guidance to NHC, some of these models did slightly better then the old GFDL system (bottom) particularly at the later forecast periods. However, the new GFDL system performed better then all of the other models at every time period for this limited set of cases.

The new GFDL package was also tested for 51 cases during the 2000 hurricane season, using the new AVN global analysis that will be operational during the 2001 season. The results for the track error, normalized with respect to CLIPER, are shown next (Fig. 5) both for the Atlantic and Eastern Pacific basin. Since the coupling with the ocean in the new GFDL model only occurs in the Atlantic basin, the East Pacific results were run uncoupled but with all the changes outlined in sections 2 and 3. In the Atlantic very little difference in track performance is noted with the new system. However, the model performance in this basin was already quite skillful, as seen in the comparison with the official forecast. In contrast, in the East Pacific, the new GFDL system run from the new AVN global model exhibited considerable improvement at all time levels beyond 24h. The improvement was statistically significant both at 48 and 72h time periods, with reduction in track error of about 20%, with reduced track error for 66 and 70% of the cases, respectively.

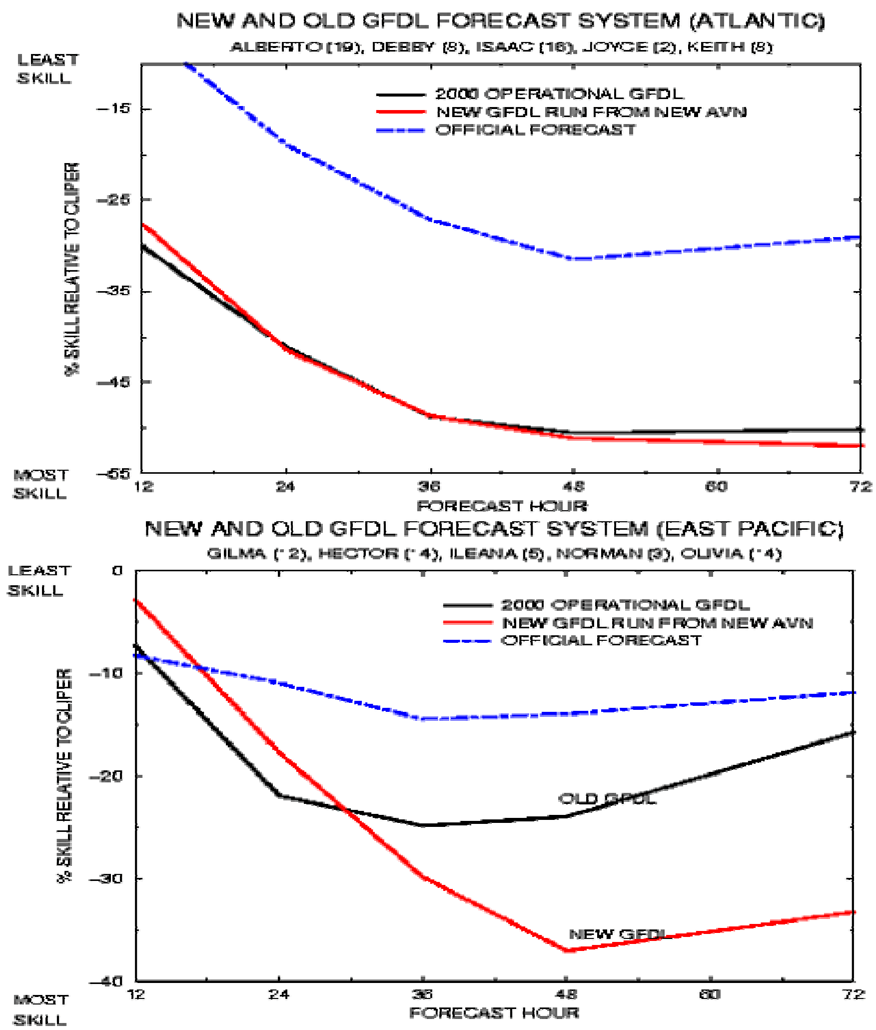

Figure 5 Plot of the track forecast skill relative to CLIPER (top), for both the operational GFDL model (black), the new GFDL forecast system (red) and the official forecast (blue dashed) for test cases from the 2000 hurricane season using the new 2001 AVN global analysis both for the Atlantic (top) and Eastern Pacific (bottom).

The 48h track error for each of the individual storms in this test set is presented next in Fig. 6.

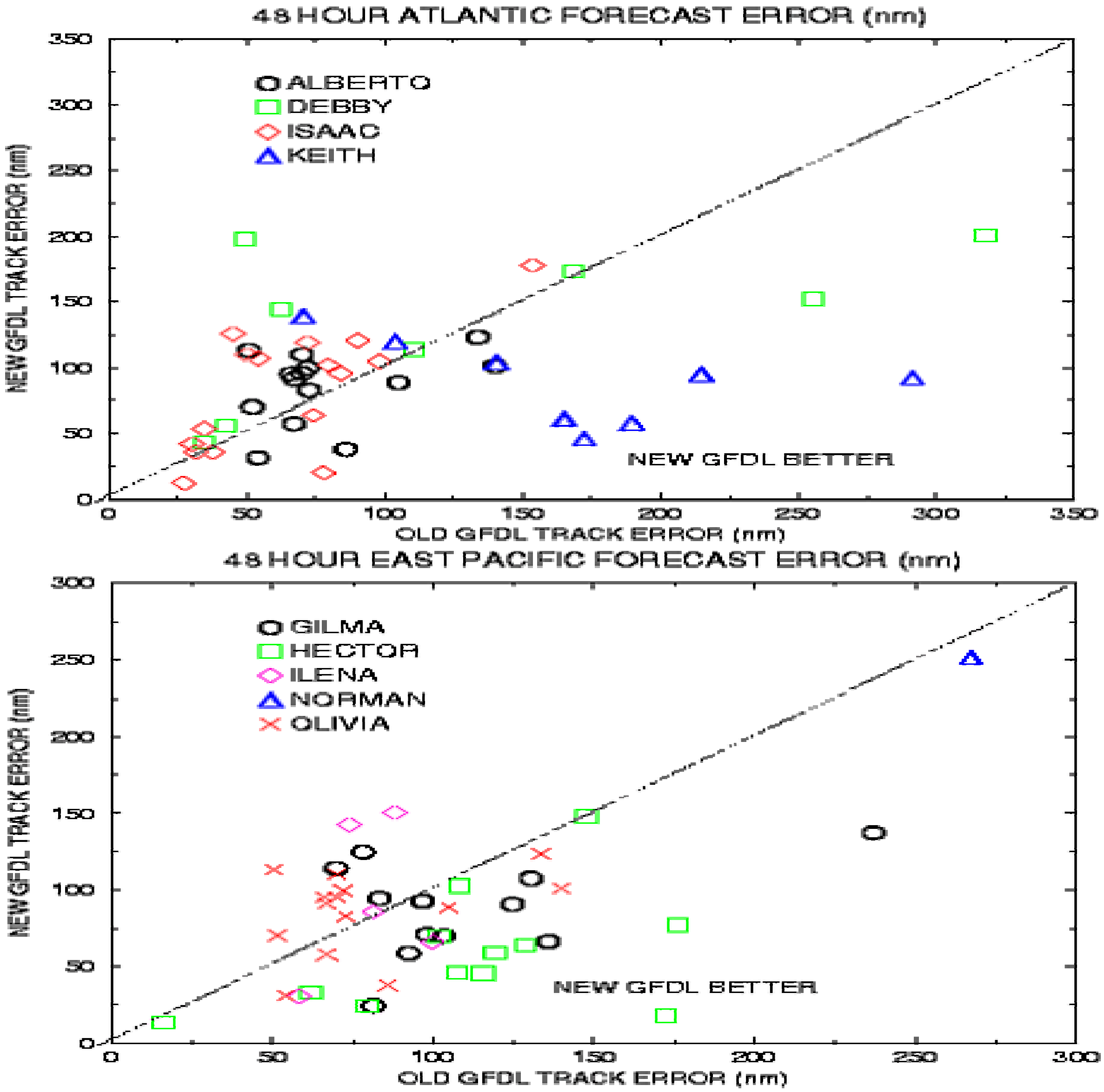

Figure 6 Scatter diagram of the 48 forecast error (nautical miles) for each of the test cases in Fig. 5 for both the Atlantic (top) and Eastern Pacific (bottom), comparing the current operational GFDL model and new 2001 version.

Much of the poor performance of the GFDL model for Hurricane Keith was dramatically reduced with the new system. Fig. 7 shows one example from the forecast at the 0000 UTC 1 October initial time. The model also performed better for Hurricanes Olivia,, Gilma and Hector in the East Pacific which had large errors in several of the operational GFDL forecasts.

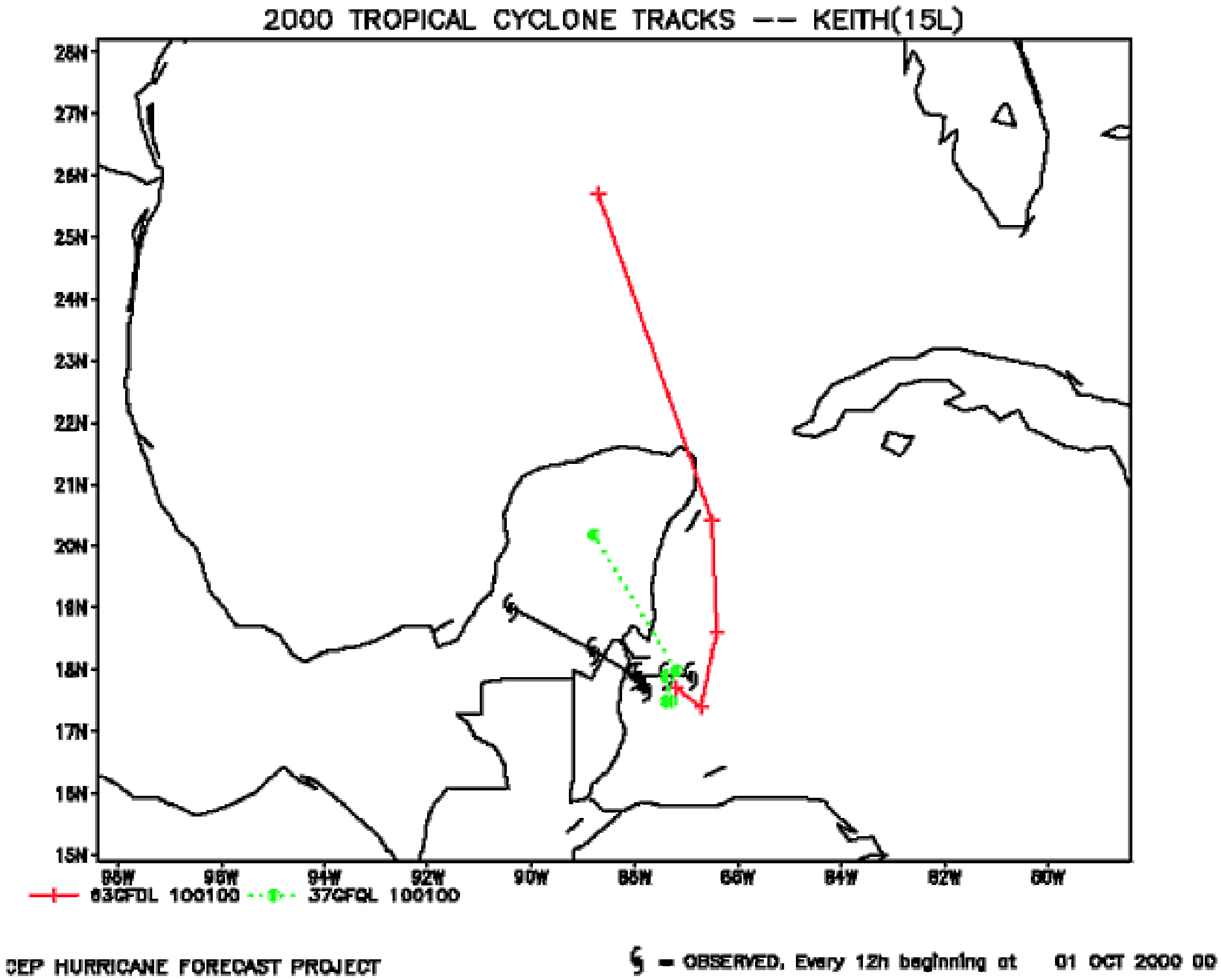

Figure 7 Forecasted storm tracks for Hurricane Keith using the operational GFDLforecast system (red) and the new GFDL forecast system (greeen dashed)
compared to the observed track (black), starting from the 0000 UTC 1 October initial time.

Finally, the improvements in the intensity forecast with the new system are shown in Fig. 8 for the test cases in the Atlantic. The very poor performance of the GFDL model during the 12-36h forecast period is dramatically reduced with the new system. Although the model still exhibited problems at forecast hour 12, the GFDL model showed skill relative to SHIFOR by 24h with the new system with skill of over 20% relative to SHIFOR at 36h. This is particularly encouraging considering the difficultly in the intensity prediction that occurred during the 2000 season. It is also encouraging that the new GFDL model performed better than the SHIPS intensity prediction model in the 36 to 72h forecast period. However, by 72h the new GFDL model performed slightly worse than the operational GFDL model. This was because of over-prediction of the storm intensity which was greater in the new system due to the improved pressure-wind relationship for strong storms. This indicates that further refinements to the model physics, particularly in the parameterization of convection and moist processes are necessary before the GFDL can be relied on for consistently skillful intensity prediction, particularly in sheared situations where the model usually tends to greatly over intensify storms. Nevertheless, it is

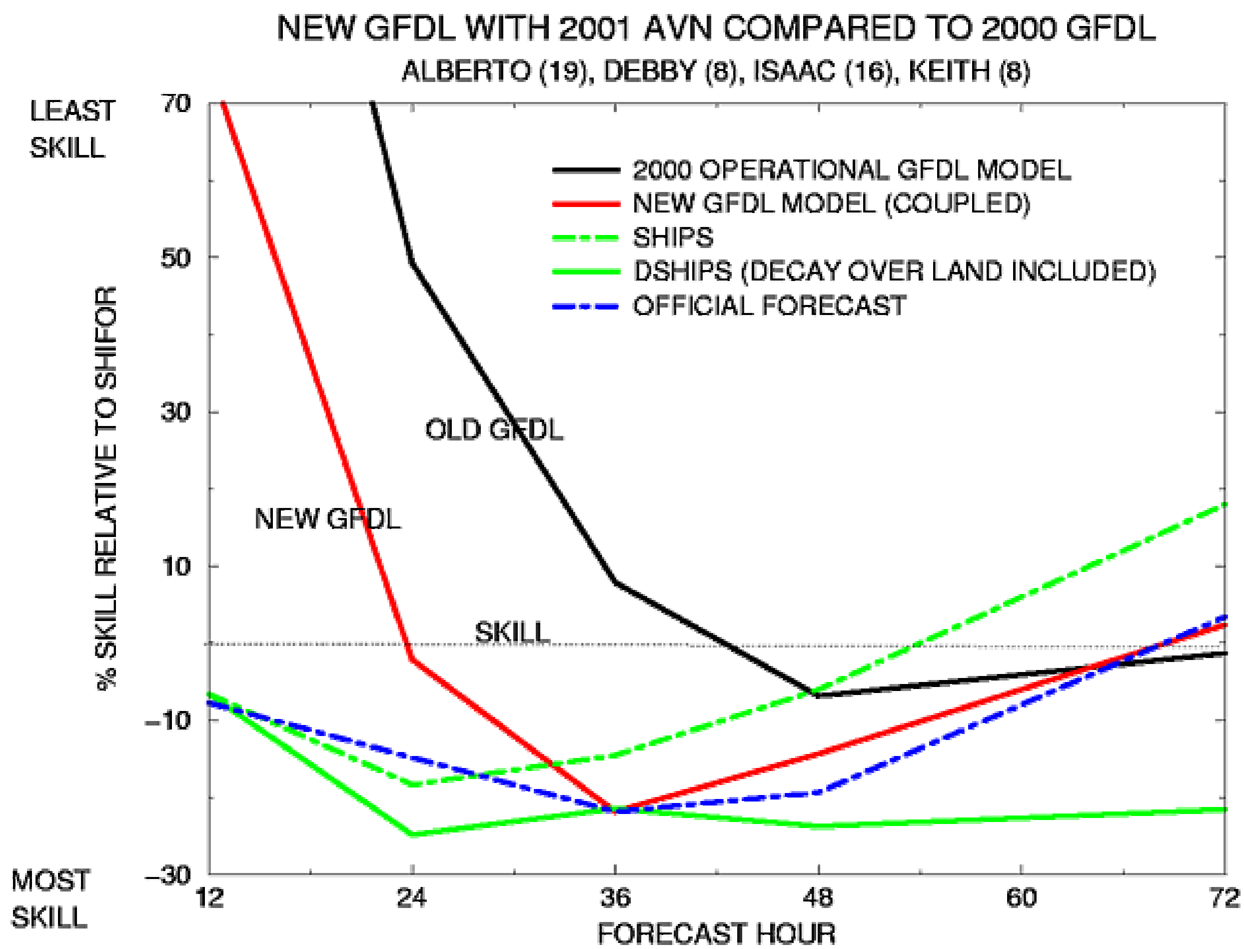

Figure 8 Plot of the intensity error relative to SHIFOR for the operational GFDL model (black), the new GFDL forecast system (red), the official forecast (blue dashed) and the SHIPS intensity model (green), for test cases from the 2000 hurricane season in the Atlantic basin using the new 2001 AVN global analysis.

anticipated that the new model will provide useful intensity prediction particularly in storms that are not undergoing strong vertical shear. This should make it a valuable tool to the National Hurricane Center, particularly in conjunction with other intensity prediction models such as SHIPS.

7.) References

Bender, M.A. and I. Ginis, 2000: Real-case simulations of hurricane-ocean interaction using a high-resolution coupled model: effects on hurricane intensity. *Mon. Wea. Rev.*, **128**, 917-946.

Blumberg, A.F. and G.L. Mellor, 1987: A description of a three-dimensional coastal ocean circulation model. In: Three-dimensional Coastal Ocean Models, Vol. 4, edited by N. Heaps, 208 pp, American Geophysical Union, Washington, D.C.

Kurihara, Y.,1973: A scheme of moist convective adjustment. *Mon. Wea. Rev.*, **101**, 547-553.

Kurihara,Y., and M.A. Bender, 1980: Use of a movable nested mesh model for tracking a small vortex. *Mon. Wea. Rev.*, **108**, 1792-1809.

Kurihara, Y., M.A. Bender, and R.J. Ross, 1993: An initialization scheme of hurricane model by vortex specification. *Mon. Wea. Rev.,* **121**, 2030-2045.

Kurihara, Y., M.A. Bender, R.E. Tuleya and R.J. Ross, 1995: Improvements in the GFDL hurricane prediction system. *Mon. Wea. Rev.,* **123**, 2791-2801.

Kurihara, Y., R.E. Tuleya and M.A. Bender, 1998: The GFDL hurricane prediction system and its performance in the 1995 hurricane season. *Mon. Wea. Rev.* ,**126,** 1306-1322.

Large, W. G., and S. Pond, 1981: Open ocean momentum flux measurements in moderate to strong wind. *J. Phys. Oceanogr.*, **11**, 324-336.

Lacis, A.A., and J.E. Hansen, 1974: A parameterization for the absorption of solar radiation in the earth's atmosphere. *J. Atmos. Sci.,* **31**, 118-133.

Lawrence, M.B., C.J. McAdie and J.M. Gross, 1997: Operational tropical cyclone track forecast verification at the National Hurricane Center. Preprints. 22nd Conference on Hurricanes and Tropical Meteorology, Ft. Collins, CO, Amer. Meteor. Soc., 475.

Mellor, G.L., and T. Yamada, 1974: A hierarchy of turbulence closure models for planetary boundary layers. *J. Atmos. Sci.,* **31**, 1791 - 1806.

Mellor, G.L., and T. Yamada, 1982: Development of a turbulence closure model for geophysical fluid problems, *Rev. Geophys. Space Phys.*, **20**, No. 4, 851-875

Miyakoda, K., and J. Sirutis, 1977: Comparative integrations of global models with various parameterized processes of subgrid-scale vertical transports: description of the parameterization. Beitrage zur Physik der Armosphare, 50, 445-448.

Rennick, M.C., 1999: Performance of the Navy's tropical cyclone prediction model in the western North Pacific basin during 1996. *Weather and Forecasting,***14,** 297-305.

Tuleya, R.E., 1994: Tropical storm development and decay: sensitivity to surface boundary conditions. *Mon. Wea. Rev.*, **122**, 291-304.